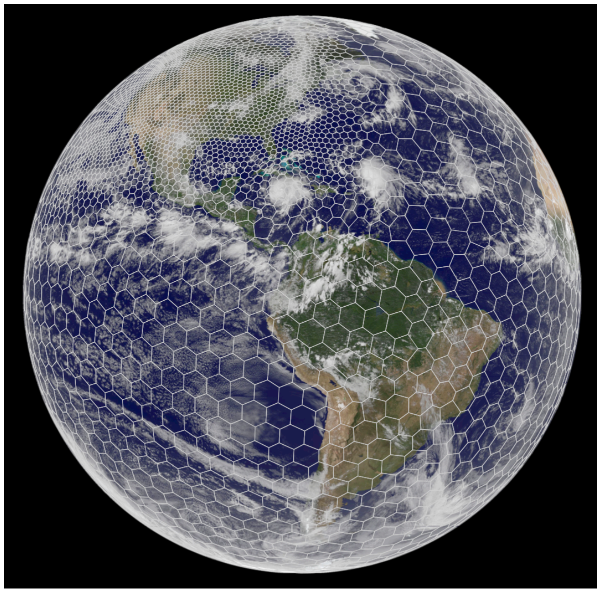
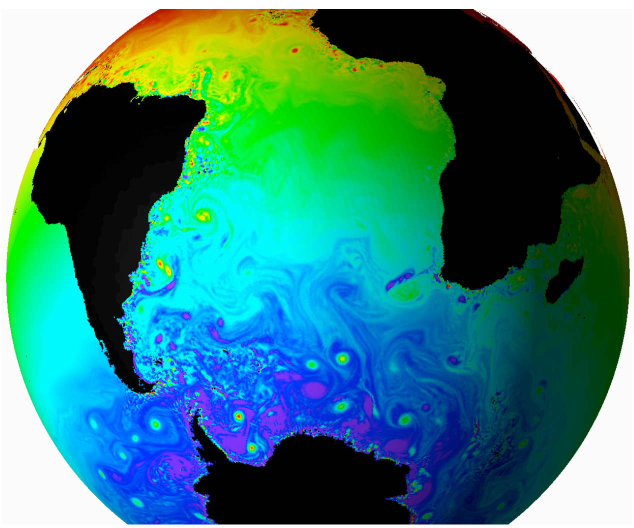
Model for Prediction Across Scales (MPAS)





MPAS
Model for Prediction Across Scales

Based on unstructured centroidal Voronoi (hexagonal) meshes using C-grid staggering and selective grid refinement.

Jointly developed, primarily by NCAR and LANL/DOE, for weather, regional climate, and climate applications

MPAS infrastructure - NCAR, LANL, others.
MPAS - Atmosphere (NCAR)
MPAS - Ocean (LANL)
MPAS - Ice, etc. (LANL and others)

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Sang-Hun Park and Laura Fowler *NCAR*
Todd Ringler *Los Alamos National Lab*
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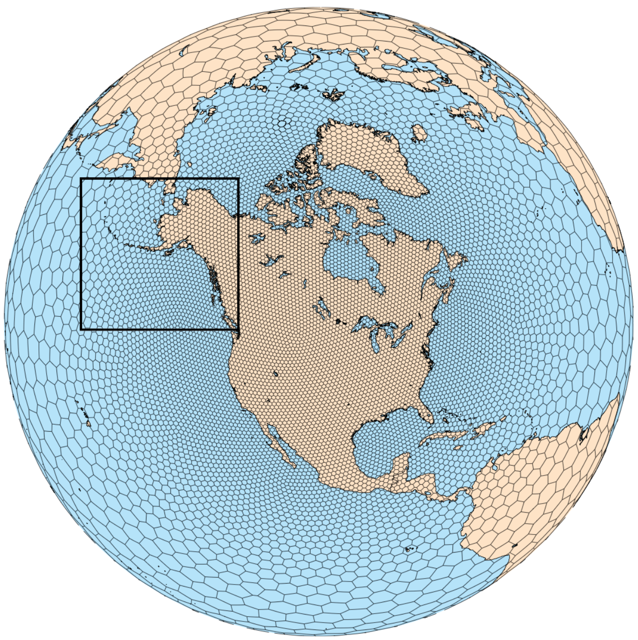
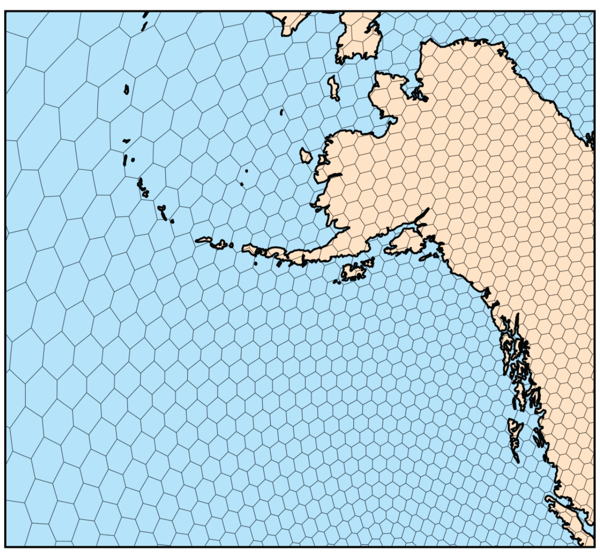
Max Gunzburger *Florida State University*
Lili Ju *University of South Carolina*

MPAS: C-Grid Spherical Centroidal Voronoi Meshes

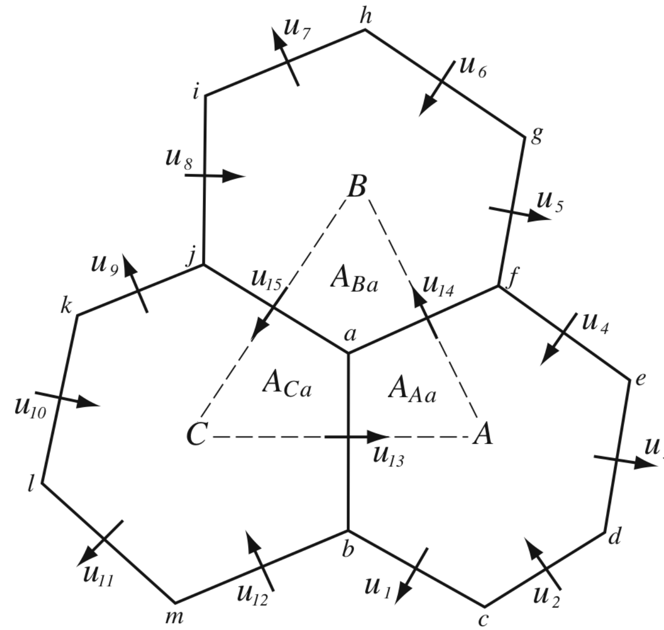




Unstructured variable-resolution mesh

Mesh generation uses a density function.

Uniform resolution – icosahedral mesh.



Centroidal Voronoi

Mostly *hexagons*, some pentagons, heptagons.

Cell centers are at cell center-of-mass.

Lines connecting cell centers intersect cell edges at right angles.

Lines connecting cell centers are bisected by cell edge.

C-grid - Solve for normal velocities on cell edges.

(optimal staggering for divergence).

Tangential velocities diagnosed using TRSK.

Equations for Atmospheric Solver

Fully compressible nonhydrostatic equations (*explicit* simulation of clouds).

MPAS Nonhydrostatic Atmospheric Solver

Nonhydrostatic formulation

Equations – fully compressible

- Prognostic equations for coupled variables.
- Generalized height coordinate.
- Horizontally vector invariant eqn set.
- Continuity equation for dry air mass.
- Thermodynamic equation for coupled potential temperature.

Spatial discretization

C-grid TRSK formulation.
Finite volume and finite difference.
Exact conservation of mass, scalar mass.
Monotonic and PD transport options.

Time integration scheme

Split-explicit Runge-Kutta (3rd order)
i.e. (HE-VI); sub-steps for acoustic modes.

Variables:

$$(U,V,\Omega,\Theta,Q_j) = \tilde{\rho}_d \cdot (u,v,\dot{\eta},\theta,q_j)$$

Vertical coordinate:

$$z = \zeta + A(\zeta)\, h_s(x,y,\zeta)$$

Prognostic equations:

$$\frac{\partial \boldsymbol{V}_H}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\boldsymbol{\nabla}_\zeta\left(\frac{p}{\zeta_z}\right) - \frac{\partial \boldsymbol{z}_H p}{\partial \zeta}\right] - \eta\,\boldsymbol{k}\times\boldsymbol{V}_H$$

$$- \boldsymbol{v}_H \boldsymbol{\nabla}_\zeta\cdot\boldsymbol{V} - \frac{\partial \Omega \boldsymbol{v}_H}{\partial \zeta} - \rho_d \boldsymbol{\nabla}_\zeta K - eW\cos\alpha_r - \frac{uW}{r_e} + \boldsymbol{F}_{V_H},$$

$$\frac{\partial W}{\partial t} = -\frac{\rho_d}{\rho_m}\left[\frac{\partial p}{\partial \zeta} + g\tilde{\rho}_m\right] - (\boldsymbol{\nabla}\cdot\boldsymbol{v}W)_\zeta$$

$$+ \frac{uU + vV}{r_e} + e\,(U\cos\alpha_r - V\sin\alpha_r) + F_W,$$

$$\frac{\partial \Theta_m}{\partial t} = -\left(\boldsymbol{\nabla}\cdot\boldsymbol{V}\,\theta_m\right)_\zeta + F_{\Theta_m},$$

$$\frac{\partial \tilde{\rho}_d}{\partial t} = -\left(\boldsymbol{\nabla}\cdot\boldsymbol{V}\right)_\zeta,$$

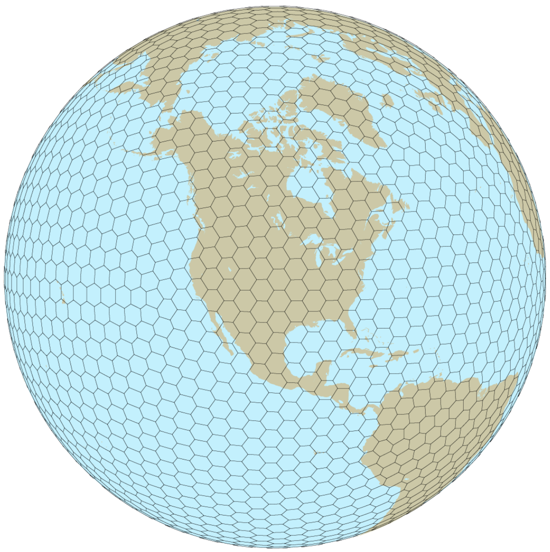
$$\frac{\partial Q_j}{\partial t} = -\left(\boldsymbol{\nabla}\cdot\boldsymbol{V}\,q_j\right)_\zeta + \rho_d S_j + F_{Q_j},$$

Diagnostics and definitions:

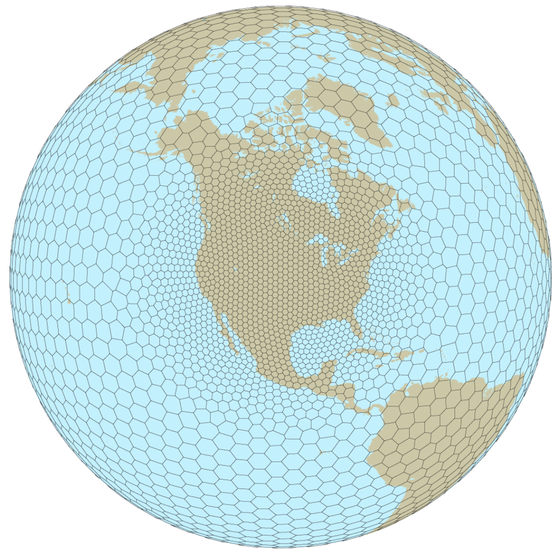
$$\theta_m = \theta\,[1 + (R_v/R_d)q_v] \qquad p = p_0\left(\frac{R_d\zeta_z\Theta_m}{p_0}\right)^\gamma$$

$$\frac{\rho_m}{\rho_d} = 1 + q_v + q_c + q_r + \ldots$$

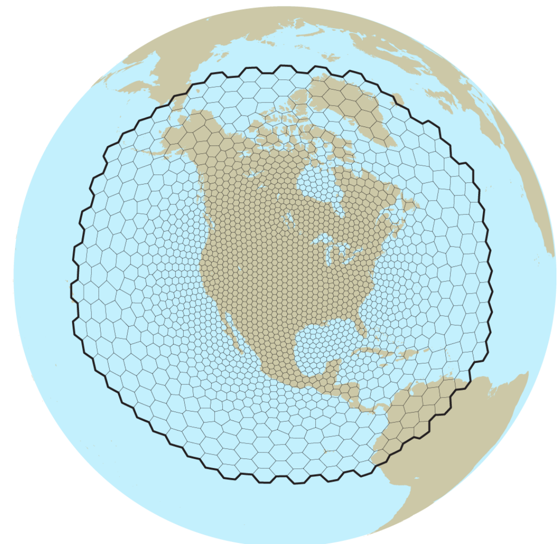
MPAS Global Mesh and Integration Options



Global Uniform Mesh



Global Variable Resolution Mesh



Regional Mesh - driven by

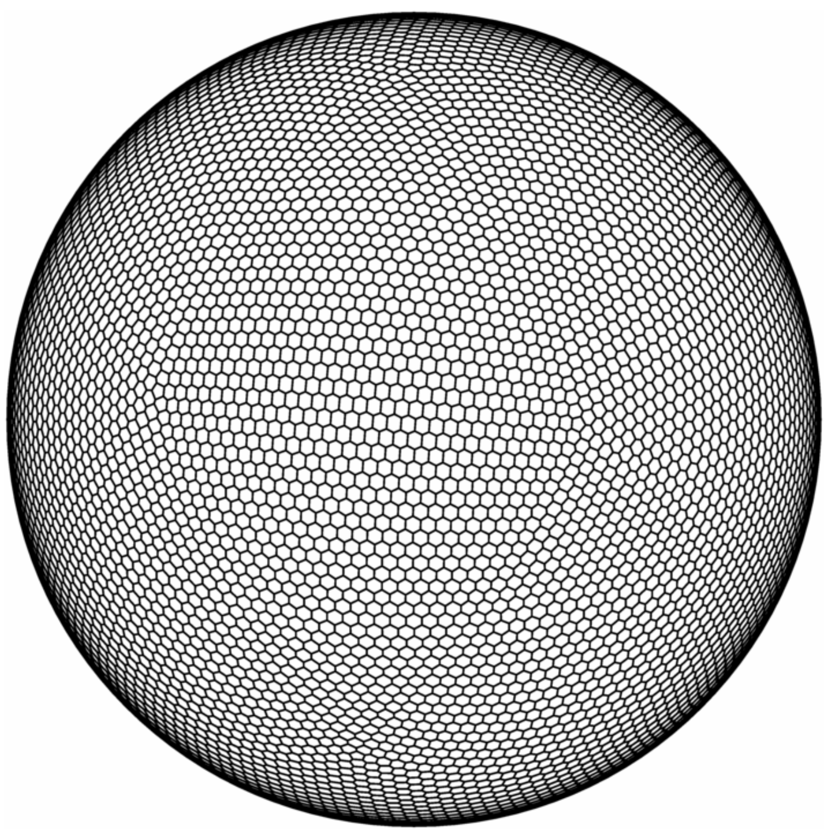
(1) previous global MPAS run
(no spatial interpolation needed!)
(2) other global model run
(3) analyses

Voronoi meshes will allow us to cleanly incorporate both downscaling and upscaling effects (avoiding the problems in traditional grid nesting) and to assess the accuracy of the traditional downscaling approaches used in regional climate and NWP applications.

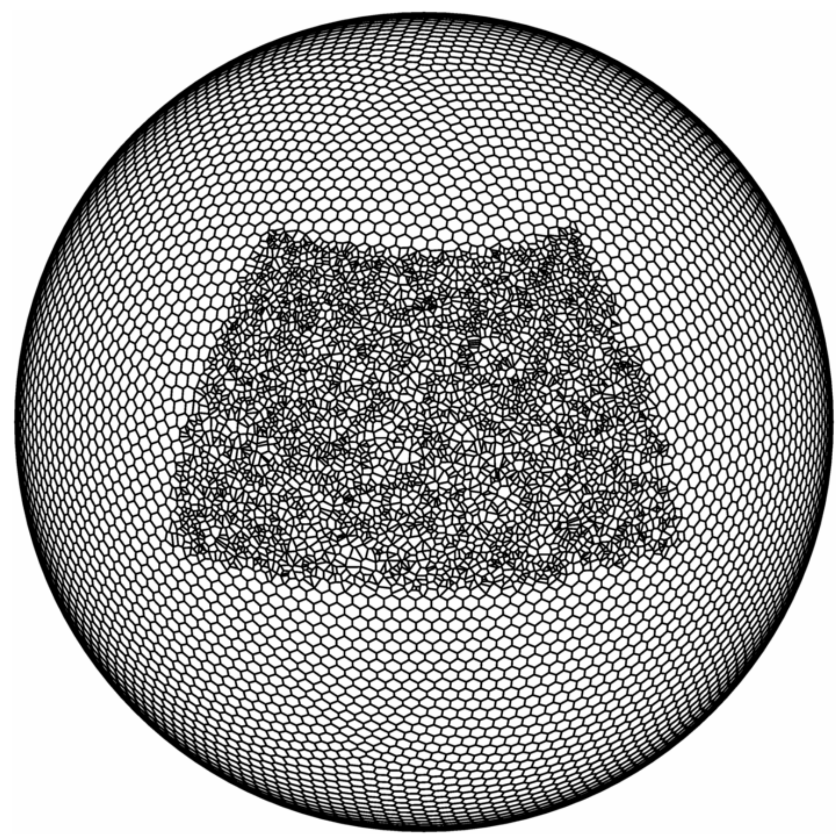
MPAS Mesh Generation

Centroidal Voronoi meshes are generated using a user-defined density function and Lloyd's algorithm (iterative).

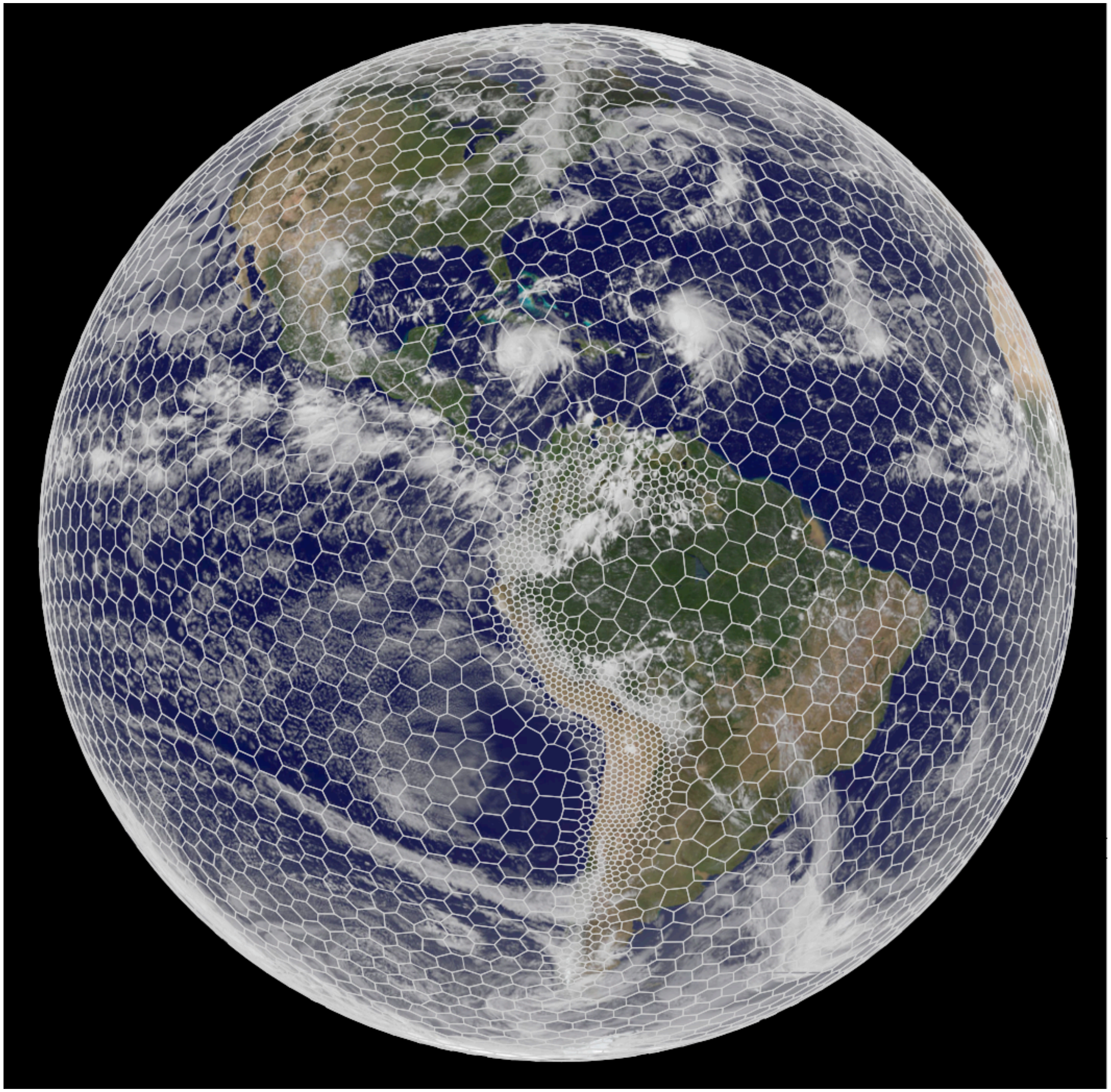
Global mesh generation



Local mesh generation



Refinement
around the Andes



Test Cases for Nonhydrostatic Atmospheric Solvers

Motivations for running test cases:

(1) Verify coding (dynamics, terrain implementation, etc.).

(2) Verify accuracy of the continuous equations
(when approximate continuous equation sets are used).

(3) Identify strengths and weaknesses of specific discretization choices within a given model
(e.g. pressure gradient calculation).

(4) Quantify the overall accuracy of a discretization or specific aspects of a discretization -
model intercomparison.

Test case design:

Tests (flows) should be physically relevant.

Correct solution must be known (analytic, numerically converged).

Test cases should be designed to highlight specific aspects of discretizations.

Test case flows/dynamics should be as simple as possible.

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Why use a nonhydrostatic solver (why high resolution?):

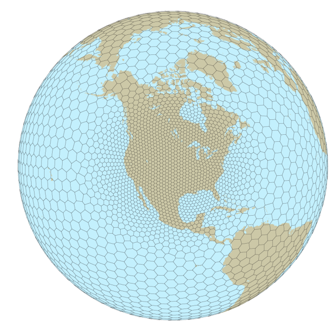
Better resolve topography and associated gravity waves (i.e. drop GWD parameterization).
Explicit simulation of deep convection (deep convection parameterizations are problematic).

The cloud-modeling and cloud-scale NWP community use gravity-wave test cases for (1), (2) and (3), but generally not for *model intercomparison* (4).

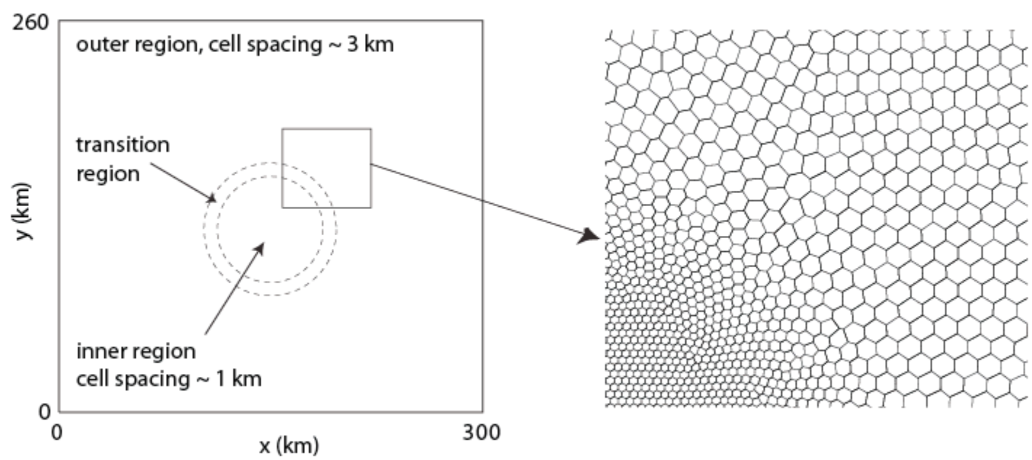
Test Cases for Nonhydrostatic Atmospheric Solvers

Because global nonhydrostatic-scale simulations are prohibitively expensive, nonhydrostatic solvers require 2D (x,z) and 3D Cartesian plane configurations for rigorous testing relevant to our end applications in weather, regional climate and climate.

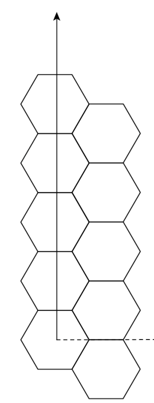
MPAS can be configured to solve on the sphere and 2D (x,z) and 3D (x,y,z) Cartesian Planes



3D (*x,y,z*) doubly periodic variable-resolution mesh



2D (y,z) simulations based on 3D doubly periodic (*x,y*) config.

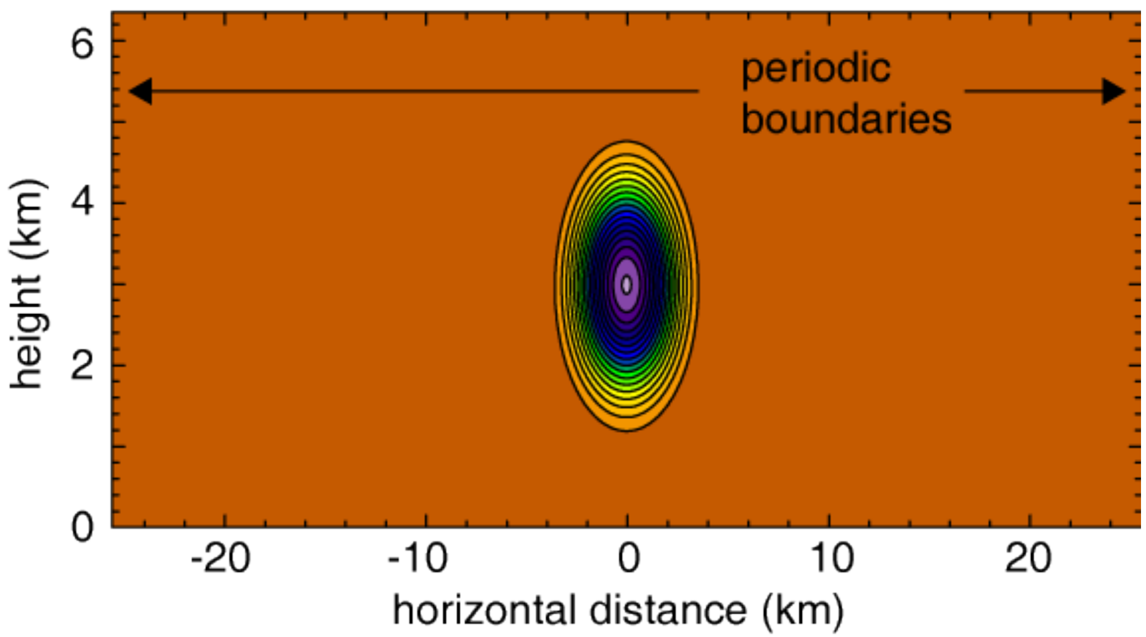


Gravity Current Simulation

(Straka et al, IJNMF, 1993)

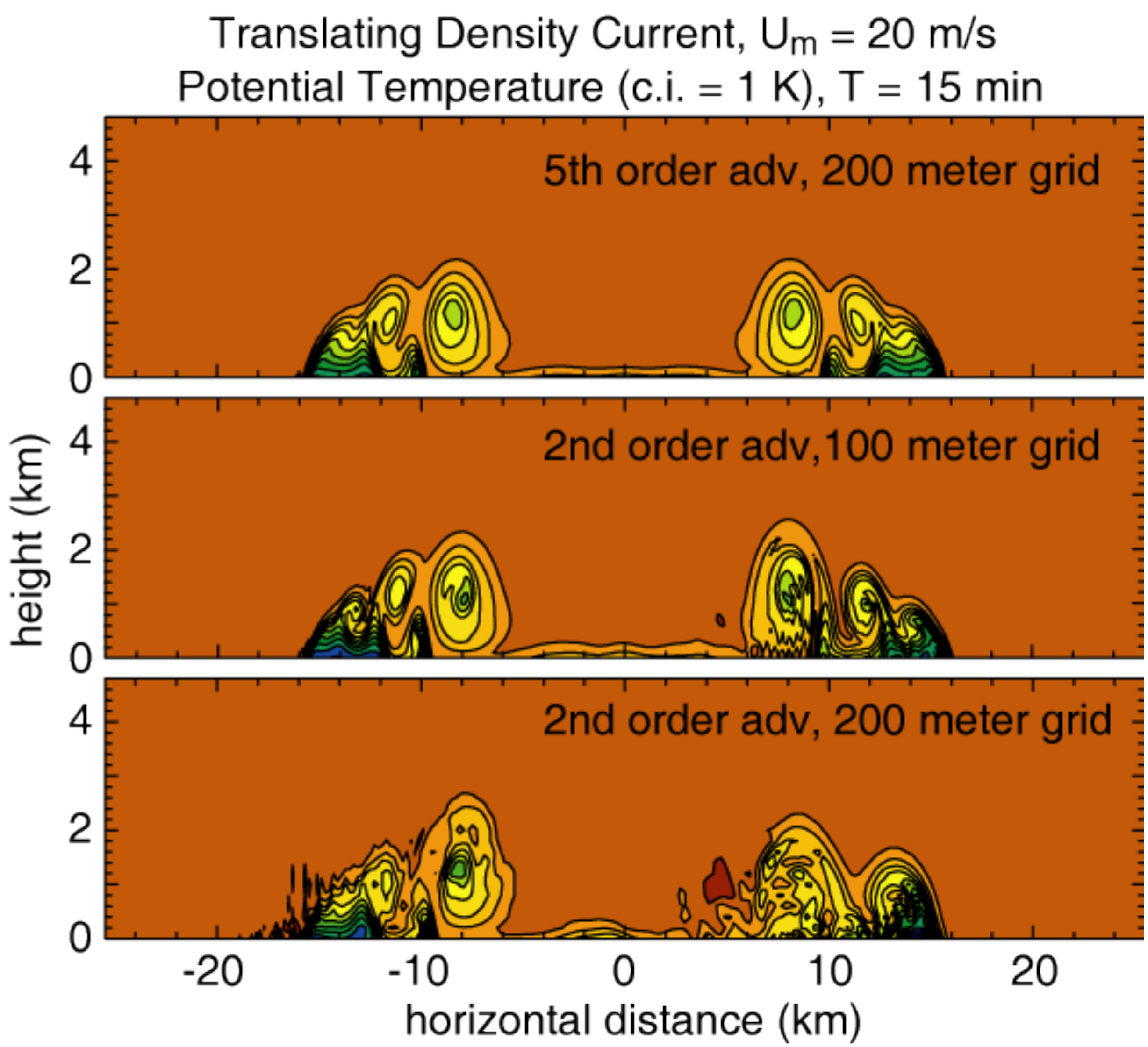
2D channel (x , z ; 51.2 x 6.4 km)
Initial state: theta = 300 K (neutral) + perturbation (max = 16.2 K)
Eddy viscosity = 75 m^2/s (constant)

Initial state, potential temperature (c.i. = 1 K)



Physical relevance: fronts, gravity currents (convective outflows)

Gravity Current Simulation
Advanced Research WRF Solutions

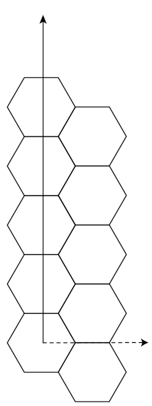


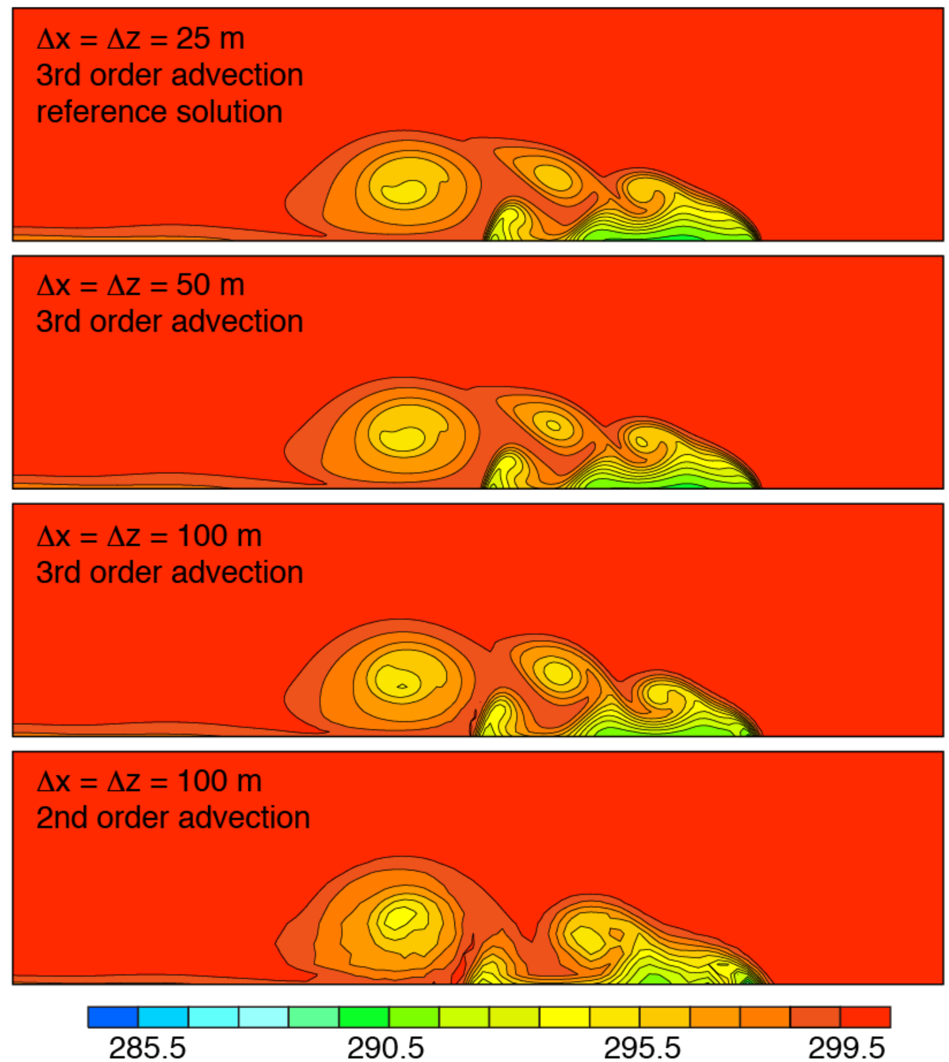
Test Cases for Nonhydrostatic Atmospheric Solvers

Gravity Current Simulation MPAS solutions

Straka et al (1993)
density current simulations

2D (y,z) simulations
Based on 3D doubly
periodic (*x*,*y*) config.



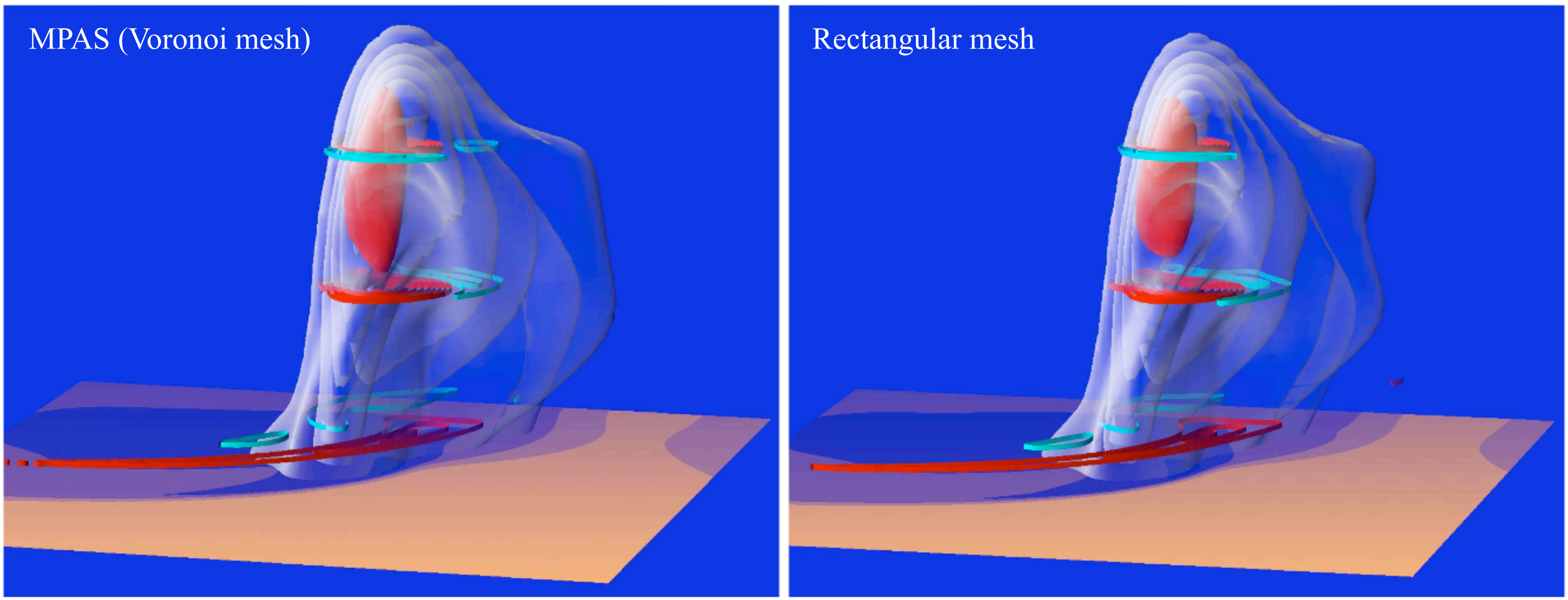


Test Cases for Nonhydrostatic Atmospheric Solvers

3D (x,y,z) tests: Squall lines, supercell thunderstorms

Supercell Tests

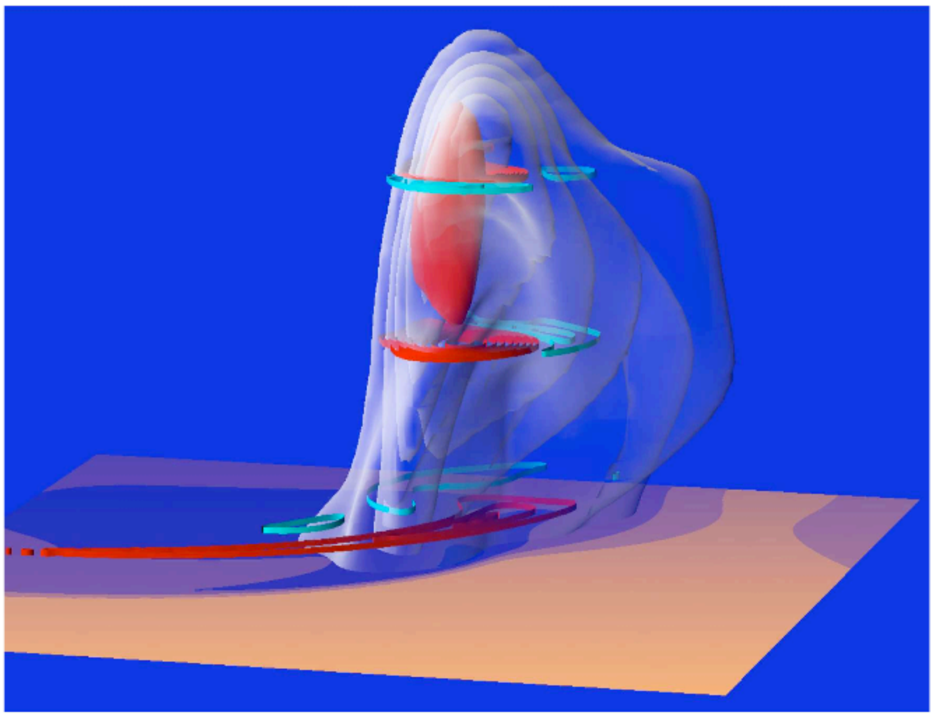
Low-level shear (0-5 km, 30 m/s), Weisman-Klemp sounding, warm-bubble perturbation,
Periodic in x and y (Lx, Ly ~ 84 km), 3D (x,y,z) simulations, Δh = 500 m

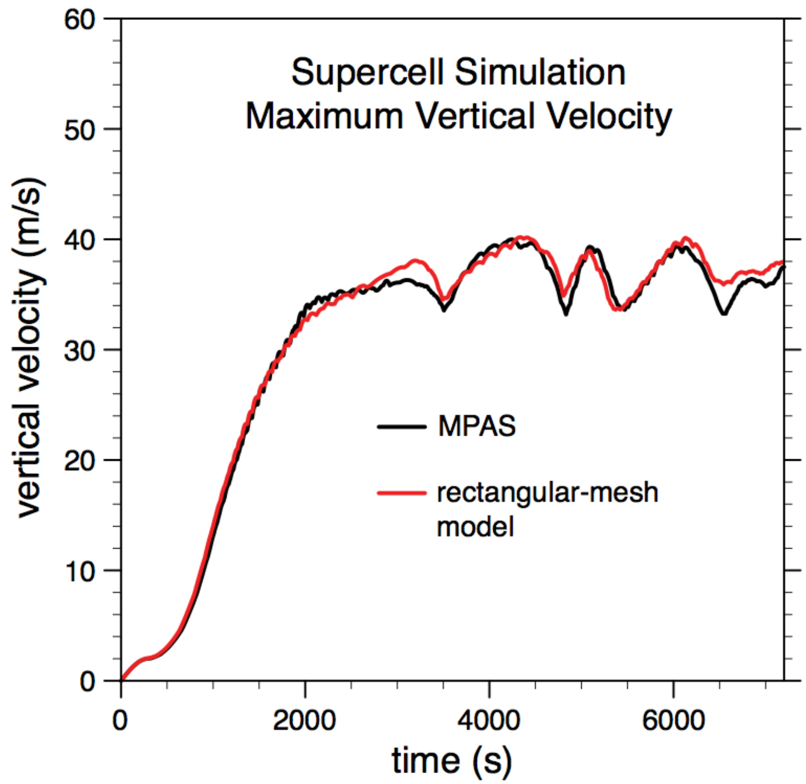


30 m/s vertical velocity surface shaded in red, rainwater surfaces shaded as transparent shells, perturbation surface temperature shaded on baseplane.

Vertical velocity contours at 1, 5, and 10 km (c.i. = 3 m/s)

Test Cases for Nonhydrostatic Atmospheric Solvers





Test Cases for Nonhydrostatic Atmospheric Solvers

Test case design:

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Nonhydrostatic test cases for the sphere?

RR-sphere gravity-wave tests are primarily coding tests.
Physically relevant Gravity currents and convection on the RR-sphere?

Because nonhydrostatic-scale simulation on the sphere are prohibitively expensive, nonhydrostatic solvers require 2D (x,z) and 3D Cartesian plane configurations for rigorous testing relevant to our end applications in weather, regional climate and climate.